REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
Feb 19 08

2. REPORT TYPE
Final Performance Report

3. DATES COVERED *(From - To)*
Feb 19 , 08-Feb 20, 08

4. TITLE AND SUBTITLE
Prognosis of Aircraft and Space Devices, Components, and Systems

5a. CONTRACT NUMBER
FA9550-08-1-0032

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Peter B. Nagy

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Aerospace Engineering and Engineering Mechanics
University of Cincinnati
Cincinnati, Ohio 45221-0070

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 North Randolph Street
Arlington, VA22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT
AFRL-OSR-VA-TR-2013-0999

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The scope of the proposed workshop was be based on, but not limited to, the recently drafted Air Force document entitled Devices, Components, and Systems Prognosis: A Proposed Discovery Challenge Thrust for AFOSR. This document envisioned an imminent paradigm shift in life prognosis for aircraft and space devices, components, and systems. Currently, the USAF relies mainly on regular inspections to detect gross defects that might cause component and system failure before the next scheduled inspection.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

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5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

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14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

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Final Report

FA9550-08-1-0032

Workshop on Prognosis of Aircraft and Space Devices, Components, and Systems

Sponsored by the Air Force Office of Scientific Research
Kingsgate Marriott Conference Hotel, University of Cincinnati, Cincinnati, Ohio
February 19 and 20, 2008

Peter B. Nagy

Department of Aerospace Engineering and Engineering Mechanics

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Cincinnati, Ohio 45221-0070

Contents

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I Objective

The main objective of the proposed *Aircraft and Space Devices, Components, and Systems Prognosis Workshop* was to bring together key researchers from academia with leading experts from the Air Force Research Laboratory (AFRL) and leading aerospace companies to discuss and identify scientifically sound directions and achievable specific targets for the anticipated Discovery Challenge Thrust (DCT) Broad Agency Announcement (BAA) to be issued by the Air Force Office of Scientific Research (AFOSR). The participants of the Workshop assembled created this report for AFOSR with recommendations for the technical content of the DCT BAA on *Life Prognosis for Aircraft and Space Devices, Components, and Systems.*

II Workshop Topics

The scope of the proposed workshop was be based on, but not limited to, the recently drafted Air Force document entitled *Devices, Components, and Systems Prognosis: A Proposed Discovery Challenge Thrust for AFOSR.* This document envisioned an imminent paradigm shift in life prognosis for aircraft and space devices, components, and systems. Currently, the USAF relies mainly on regular inspections to detect gross defects that might cause component and system failure before the next scheduled inspection. These inspections are not only interruptive of service, but also very expensive and might case additional damage in critical components that otherwise would have remained in service without significant danger of failure. In the future, the USAF would like to develop *state awareness* monitoring capabilities that could enable accurate prediction of the remaining service life and future performance capability of critical components as well as be used to take specific corrective actions to assure mission completion and minimize operating cost and risk.

This workshop discussed the various issues and ideas presented in the above mentioned preliminary draft document and considered their physical feasibility and relative importance. Additional ideas were suggested to supplement or replace some of those in the original document and various means to achieve the stated goals were debated. The topics were focused on airframe and turbine engine issues, but other, e.g., space applications, were also considered briefly.

III Workshop Relevance to AFOSR

In its original form, the draft document represented the USAF's "wish list" concerning life prognosis and did not identify specific research directions or targets for how these ambitious goals could be achieved. Some of these goals might be achievable via continued incremental technical improvements of existing structural health monitoring (SHM) and nondestructive evaluation (NDE) methods, others might require targeted fundamental research in physics, materials science, and other related principles, and some might turn out to be completely unfeasible because of fundamental physical limitations. The workshop held at the University of Cincinnati between February 19 and 20, 2008, discussed the general approach outlined in the original draft and screened the presented ideas for feasibility and relative importance. Based on presentations and discussions during the workshop, additional ideas were suggested to supplement or replace some of those in the original document.

The relevance of this workshop for AFOSR lies primarily in the interdisciplinary peer review of the expected DCT BAA by key researchers from academia who are most likely to respond to the solicitation and later participate in the ensuing research projects. Such a direct interchange of ideas among all the key participants of this initiative would not have been possible later in the competitive phase of the DCT BAA.

IV Workshop Web Site

http://www.ase.uc.edu/~pnagy/NDE/AFOSR%20Prognosis%20Workshop

Prognosis of Aircraft and Space Devices, Components, and Systems

Sponsored by the Air Force Office of Scientific Research
Kingsgate Marriott Conference Hotel, University of Cincinnati, Cincinnati, Ohio
February 19 and 20, 2008

Objective:

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Workshop Topics:

The scope of the proposed workshop will be based on, but not limited to, the recently drafted Air Force document entitled *Devices, Components, and Systems Prognosis: A Proposed Discovery Challenge Thrust for AFOSR*. This document envisions an imminent paradigm shift in life prognosis for aircraft and space devices, components, and systems. Currently, the USAF relies mainly on regular inspections to detect gross defects that might cause component and system failure before the next scheduled inspection. These inspections are not only interruptive of service, but also very expensive and might case additional damage in critical components that otherwise would have remained in service without significant danger of failure. In the future, the USAF would likc to develop *state awareness* monitoring capabilities that could enable accurate prediction of the remaining service life and future performance capability of critical components as well as be used to take specific corrective actions to assure mission completion and minimize operating cost and risk. The workshop will discuss the various issues and ideas presented in the above mentioned preliminary draft document and consider their physical feasibility and relative importance. Additional ideas will be suggested to supplement or replace some of those in the original document and various means to achieve the stated goals will be debated. The topics will be focused on airframe and turbine engine issues, but other, e.g., space applications, will be also considered.

Registration, Accommodation, Travel:

Advance registration will be required via e-mail before February 10, 2008, but there is no registration fee. A special group rate is available at the Kingsgate Marriott Conference Hotcl for the participants of the workshop for the nights from February 02.18.08 through 02.20.08. Limited funds are available to cover some of the travel expenses of invited participants in case they need financial assistancc to attend thc workshop.

Program

Abstracts

Registration

Hotel Reservation

List of Participants

Discovery Challenge Thrust Draft

Workshop Recommendations

University of Cincinnati

V Conference Program

1st day, Tuesday, February 19, 2008

Session 1, Paradigm Shift in Life Prognosis

Peter B. Nagy, Chairperson

10:00 am	Welcome Note, Carlo Montemagno, Dean of Engineering, University of Cincinnati
10:05 am	Kick-off Remarks, Victor Giurgiutiu, AFOSR
10:15 am	Keynote Lecture: Operational Needs for a Paradigm Shift in Life Prognosis, Robert S. Fredell Colonel, HQ AF/ST
11:00 am	"Opportunities and Challenges in Damage Prognosis for Materials and Structures in Complex Systems," James M. Larsen, Reji John, and Eric Lindgren, AFRL/RX
11:30 am	"Prognosis – A Vision for 2030," Thomas A Cruse, DARPA/DSO Consultant, AFRL (retired)
12:00 pm	lunch break

Session 2, OEM and End-User Perspectives

Thomas A Cruse, Chairperson

1:00 am	"Effective State Awareness Information is Enabling for System Prognosis," Mark Derriso, AFRL/RBSA
1:20 pm	"Challenges Associated with Implementing an Integrated Structural Health/Life Management System for Aerospace Structures," Joe P. Gallagher, Aeronautical Systems Center (retired)
1:40 pm	"Airframe Manufacturer's Perspective of Materials State Awareness," Richard Bossi and Kent Ruffing, The Boeing Company
2:00 pm	"The Quest for Personalized Engine Maintenance," Edmund Hindle, General Electric Aviation
2:20 pm	break

Session 3, Prognostics

Dave L. McDowell, Chairperson

2:40 pm "Predicting Fatigue Processes in Aluminum Alloys Using Stochastic Multi-Scale Simulations," Paul Wawrzynek and Anthony Ingraffea, Cornell University

3:00 pm "Physically-Based Modeling in State-Awareness Monitoring Strategies," Dave McDowell, Georgia Tech

3:20 pm "The Witness Sample Approach to Prognostics," Alten Grandt, Purdue University

3:40 pm "Impact of Multiple On-Board Inspections on Cumulative Probability of Detection," Harry Millwater, University of Texas at San Antonio

4:00 pm "A New Approach for Investigating Crystal Stresses that Drive the Initiation of Fatigue-Induced Defects in Structural Alloys," Matt Miller and Paul Dawson, Cornell University

4:20 pm break

Session 4, Goals and Specific Targets

James M. Larsen, Chairperson

4:40 pm roundtable discussion

6:00 pm end of session

2nd day, Wednesday, February 20, 2008

Session 5, Physical Foundations

Kumar V. Jata, Chairperson

9:00 am "Role of Environment in Mechanism-based Modeling of Airframe Fatigue," Rick P. Gangloff, University of Virginia

9:20 am "Multiphysics Foundations for Material State Change Prognosis in Material Systems," Ken L. Reifsnider, F. Chen, and X. Xue, University of South Carolina

9:40 am "Electromagnetic Materials State Awareness Monitoring," Peter B. Nagy, University of Cincinnati

10:00 am “Nonlinear Ultrasonic Materials State Awareness Monitoring,” Larry J. Jacobs and Jianmin Qu, Georgia Institute of Technology

10:20 am break

Session 6, Technical Capabilities

Mark J. Schulz, Chairperson

10:40 am “Exploring the implications of a Bayesian approach to Materials State Awareness,” Bruce Thompson, Iowa State University

11:00 am “An Interdisciplinary to Understanding “Dwell Fatigue” in Ti Compressor Rotor Alloys,” Jim Williams, Amit Bhattacharjee, Somnath Ghosh, Mike Mills, and Stan Rokhlin, Ohio State University

11:20 am “An Unified Approach to Structural Health Management and Damage Prognosis of Metallic Aerospace Structures,” Aditi Chattopadhyay, Arizona State University

11:40 am “Damage State Awareness in Composite Laminates Via Ultrasonic Guided Waves,” Cliff Lissenden and Joe Rose, Pennsylvania State University

12:00 pm lunch break

Session 7, Feasibilities

R. Bruce Thompson, Chairperson

1:00 pm roundtable discussion
2:40 pm break

Session 8, Recommendations for DCT BAA

Victor Giurgiutiu, Chairperson

3:00 pm roundtable discussion

5:00 pm closing remarks, Victor Giurgiutiu, AFOSR

5:10 pm end of session

VI Abstracts

1st day, Tuesday, February 19, 2008

Session 1, Paradigm Shift in Life Prognosis
Peter B. Nagy, Chairperson

Keynote Lecture: Operational Needs for a Paradigm Shift in Life Prognosis, Robert S. Fredell Colonel, HQ AF/ST

The US Air Force operates a 6000-aircraft fleet with an average age of 25 years, while carrying out a recapitalization program that replaces only about 60 aircraft per year. To maintain flight safety, USAF maintenance crews carry a high structural inspection burden to support the successful damage-tolerance-based Aircraft Structural Integrity Program. Recent experience with the F-15 fleet has shown that even a high burden of inspections will not assure flight safety if the inspections are done in the wrong place. Simultaneous breakthroughs on three fronts: structural materials, heavy maintenance, and airframe prognosis offer dramatic new opportunities to the design and development of "carefree" transport wing structures for new aircraft and for the structural life extension of aging aircraft. The "carefree structures" concept, first proposed by Hinrichsen, suggests that truly optimized structures are not designed simply for minimum weight; rather, they are optimized for minimum life cycle costs. This requires material durability, extremely long damage-free lives and freedom from corrosion, along with resistance to impact and lightning and designed-for simplified inspection and repair. Combined with a design for effective state awareness allows an innovative high-velocity maintenance approach that simultaneously offers dramatic life cycle cost-saving benefits over legacy designs while ensuring a high level of safety and availability.

Opportunities and Challenges in Damage Prognosis for Materials and Structures in Complex Systems, James M. Larsen, Reji John, and Eric Lindgren, AFRL/RX

Key challenges, motivations, and historical perspective for prognosis of Air Force systems are outlined from the perspectives of materials and structures in turbine engines and aircraft. The overarching long-term vision for prognosis offers tremendous opportunity to attack the costs of system maintenance and operation, while also enabling the development of new systems having unprecedented capability and reliability.

Prognosis – A Vision for 2030, Thomas A Cruse, DARPA/DSO Consultant, AFRL (retired)

Over the next 25 or so years, the nation will field a variety of new air, space and cyber systems to support the defense needs of the nation. Air vehicles, advanced propulsion, and revolutionary avionics and ISR (intelligence, surveillance, and reconnaissance) electronics packages of the future require, for both cost and readiness purposes, the ability to be fully self-diagnostic. That is, from the mission commander to the maintainer to the logistician (supply chain), the operators responsible for each air vehicle, turbine engine, and electronics package must be informed in real-time of the health status and future capability of the system. Prognosis 2030 is an attempt to motivate the funding of a basic research program to achieve revolutionary changes in the three fundamental elements for prognosis – state modeling that translates system environment history into response at the material damage level, the ability to fully characterize the as-processed and

manufactured material state (a so-called material/system "fingerprint") for each system element, and the idea of a "virtual sensing" strategy that tightly integrates these with new approaches to traditional NDE to define the current and future state of the system as a digital state sensor. The basic research program to support this vision is one that needs to be built around the key challenges where fundamental breakthroughs are required and possible.

Session 2, OEM and End-User Perspectives
Thomas A Cruse, Chairperson

Effective State Awareness Information is Enabling for System Prognosis, Mark Derriso, AFRL/RBSA

The Department of Defense has recently placed emphasis on the development of Integrated Systems Health Management (ISHM) techniques. The ultimate goal of ISHM is to provide a system level capability assessment along with a prognosis regarding the potential risk and success of future missions. To meet this goal, ISHM requires an accurate diagnosis of the current condition of the various subsystems. Consider, for example, the health of the air vehicle structure. The structural design includes numerous uncertainties during the design process. Design techniques are utilized to accommodate for these uncertainties, resulting in a design with an initial prognosis of no failure during the design life. Over time, however, requirements change and the subsystem and system prognosis change. This presentation outlines the role of effective state awareness in enabling system prognosis and discusses the basic technical challenges relating to diagnosing the current state of the vehicle subsystems.

Challenges Associated with Implementing an Integrated Structural Health/Life Management System for Aerospace Structures, Joseph P. Gallagher, Aeronautical Systems Center (retired)

Damage characterizes and defines the material state that directly relates to structural health and to remaining life for airframes. The aircraft structural integrity program (ASIP), as defined by MIL-STD-1530C, provides the framework and processes associated with the initial and continuing airworthiness certification of USAF airframe structures. The ASIP framework and processes facilitate the characterization of the damage state in airframes (aircraft structures) as a function of time in-service. The concept of multiple methods for characterizing the damage state is presented. These multiple methods include: 1) the on-board usage monitoring method (provided by virtual sensors); 2) the off-board damage monitoring method (based on maintenance/inspection data collection; and, 3) storage of damage information), and the on-board damage monitoring method (provided by damage-event sensors). By focusing on the fatigue mechanism and similar aging mechanisms, several types of damage distributions are identified. The presentation identifies several serious challenges associated with characterizing the current state of damage and its accurate projection into a future state. The presentation provides some guidance on the way ahead.

Airframe Manufacturer's Perspective of Materials State Awareness, Richard Bossi and Kent Ruffing, The Boeing Company

Aircraft mission readiness capability over the lifetime of an airframe is critical. Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) technologies play an increasingly interdependent role in providing the material state awareness information used to decide mission readiness. A number of development activities are needed to effectively integrate NDE and SHM. One particularly important area is the service data records information and lessons learned from those records for aircraft airframes and systems.

The Quest for Personalized Engine Maintenance, Edmund Hindle, General Electric Aviation

The United States Air Force is in the midst of a serious operational cost trend that if not corrected will result in a lose-lose situation for both the Air Force and the OEM. A revolutionary paradigm shift must take place to reverse the aircraft sustainment demand for funding. A prognosis based life approach can go a long way towards reversing the operating cost trend but has scientific and technical issues that must be addressed. Current fleet management capability is constrained by uncertainty in the current state of the individual aircraft engines. The ability to sense or measure the damage state of an individual part is limited at best. Further, specific part operational severity is not captured with the current lifing process, hence many components are not operating to their life entitlement because the life is based on fleet weighted average missions. Unlike the fixed interval inspections currently being performed, precise assessment is required for prognosis-based lifing. The key considerations in this assessment are 1) the fidelity of the analysis tools 2) the definition of the boundary conditions (or environmental conditions used by the analysis tools) 3) improved understanding of diagnostics and engine faults with enhanced troubleshooting tools.

Session 3, Prognostics
Dave L. McDowell, Chairperson

Predicting Fatigue Processes in Aluminum Alloys Using Stochastic Multi-Scale Simulations, Paul Wawrzynek and Anthony Ingraffea, Cornell University

The goal of this research is to develop physics-based models for stochastically simulating all stages of microstructurally small fatigue crack formation in aluminum alloys. The salient features of our approach are: A) The use of statistically representative, realistic microstructures as a starting point for our simulations; B) The use of polycrystal plasticity models to compute accurately stress and strain fields in polycrystals using the finite element method; and C) The use of an explicit geometric representational approach in a multi-scale methodology. At each length scale, fatigue crack precursors, such as grain boundary or particle decohesion, are represented geometrically in the finite element model, and allowed to evolve through changes in the underlying geometric and mesh models. We will report on progress in development, verification, and validation of our probabilistic simulation models, and show example simulations specific to aluminum alloy 7075-T651.

Physically-Based Modeling in State-Awareness Monitoring Strategies, Dave McDowell, Georgia Tech

The role of physically-based models for crack formation and early growth near hot spots is considered in terms of its contribution to state-of-awareness of aerospace propulsion and airframe structural applications. It is envisioned that computational microstructure-scale modeling of material deformation and damage will be combined with simulations and experiments characterizing signals from sensors interrogating critical locations in metallic systems, and then linked to algorithms for predicting remaining life with consideration of uncertainty.

The Witness Sample Approach to Prognostics, Alten Grandt, Purdue University

The goal of this talk is to overview a proposed "witness sample" method that could provide a cost effective approach for monitoring structures for evidence of potential fatigue and/or corrosion damage. The approach employed here is to attach a small pre-cracked coupon (crack gage) to the structural member of interest. Structural loads are transferred to the coupon and result in measurable crack growth in the coupon. Fracture mechanics techniques enable one to relate crack growth in the coupon with the nucleation and/or extension of an assumed structural crack. Thus, the crack gage provides a simple and rapid nondestructive technique to assess the potential for fatigue damage in the structural member of interest. Since the witness sample is also sensitive to the same thermal-chemical environment seen by the structure, it also monitors the detrimental effects of environment on structural integrity. The end result would be a simple nondestructive evaluation technique to enable critical maintenance and repair decisions by flight line personnel.

Impact of Multiple On-Board Inspections on Cumulative Probability of Detection, Harry Millwater, University of Texas at San Antonio

This research examines the simulation of recurring automated inspections resulting from simulated on-board "crack" sensors, and their potential effect on reducing the probability-of-fracture of structural components. We assert that recurring inspections for an automated system should be modeled as dependent with respect to the first inspection due to the largely repeatable aspects of the sensor and data collection system. This assertion has a large effect on the computed probability of detecting a crack and alleviates the substantial overprediction of sensor efficacy generated using the assumption of independent inspections for automated systems. Furthermore, it is demonstrated that the fundamental feature that determines the efficacy of a recurring automated on-board sensor is the probability of detecting a crack of critical size, i.e., the size that will cause fracture, and this feature is by and large separate from the shape of the POD curve. This information can be used to determine the required accuracy of an on-board automated inspection to achieve a specified reliability of a structural component.

A New Approach for Investigating Crystal Stresses that Drive the Initiation of Fatigue-Induced Defects in Structural Alloys, Matt Miller and Paul Dawson, Cornell University

Fatigue failure continues to be among the most challenging limitations for the design of aerospace engines and structures. While post-mortem microstructural analyses can provide insight into specific fatigue-related accidents - they yield little information that will improve our ability to actually predict fatigue failures. Design for fatigue continues to follow conservative, yet costly guidelines. Due to complicated material microstructures and anisotropic single crystal

properties, the prediction of microcrack initiation within polycrystalline metallic alloys and composite systems has proven illusive. This talk describes a hybrid experimental-simulation project – currently being funded by AFOSR - that focuses on predicting the cyclic loading-induced evolution of micromechanical state that leads to microcrack initiation. The key aspects of the methodology are: i) in-situ synchrotron x-ray diffraction / cyclic loading experiments to measure the evolving distribution of three-dimensional stress states at the scale of a single crystal within the aggregate, ii) elasto-viscoplastic polycrystal plasticity simulations that discretize each crystal using finite elements and iii) a cohesive digital framework for combining and comparing simulated and experimental results. The dynamic nature of the in-situ experiments, the computationally intensive multiscale simulations and the combined experimental and numerical aspects of the overall approach should make the description of this project relevant to the discussion around the proposed BAA for real time assessment of aerospace structural health.

2nd day, Wednesday, February 20, 2008

Session 5, Physical Foundations
Kumar V. Jata, Chairperson

Role of Environment in Mechanism-based Modeling of Airframe Fatigue, Rick P. Gangloff, University of Virginia

Environment impacts the driving forces and damage mechanisms for each stage of fatigue in structural metals including modern aluminum alloys. Such effects must be incorporated in inspection/sensing, properties data, and physics-based damage mechanism modeling inputs to next-generation performance prognosis. With notable exceptions, environmental effects on structural integrity are not addressed quantitatively in life management methods for DoD and civilian structures. Fundamental uncertainties are associated with:

• Environment electrochemistry spectra that vary with base and flight operations, and affect damage accumulation in transient modes.
• Localized-occluded geometric and chemical factors that are associated with a corroded surface and confound state sensing of features governing transition to fatigue cracking.
• Physics-based modeling of the distribution of lives for transition from corrosion to fatigue crack formation and early growth that parallels cutting edge work on microstructure-scale defect-initiated damage accumulation.
• Physics-based modeling of gradated nano-to-micro scale damage at a fatigue crack tip that is limited because fundamental damage mechanisms and failure criteria are not quantified.

Research on mechanisms of these environment-fatigue interactions is highlighted to initiate discussion of environmental effects in prognosis and to extend fundamental plasticity modeling of the stages of fatigue.

Multiphysics Foundations for Material State Change Prognosis in Material Systems, Ken L. Reifsnider, F. Chen, and X. Xue, University of South Carolina

Material systems are nano-structured heterogeneous materials in which there is a "composite effect," a behavior or performance that is more than the linear sum of that of the constituents. In

such systems, discrete events, such as damage or degradation – or other changes of material state, are typically spatially distributed throughout most of the life of the material in an applied environment. The advent of functional material systems, such as fuel cells, electrolyzers, and many membrane-based systems (for processing, medical devices, etc.) has taught us that these distributed events are characterized by changes in many physical aspects of the material state, such as mechanical integrity, conductivity, density, electrical and magnetic properties, and diffusion / transport characteristics. These state changes are often coupled, by temperature, mass transport, heat transport, etc. Analysis of such coupled phenomena has become an important element of engineering. "Multiphysics analysis" is now supported by well established methodology, and even some commercial codes. However, applications of such analysis methods are somewhat disperse, and understandings of the problems addressed by those methods are somewhat remedial at this point. This talk will examine the fundamental concept of using multiphysics methods and analysis to link mechanical changes in state (e.g., distributed 'damage') to other multiphysics-based coupled changes in state using the experimental methodology referred to as electrochemical impedance spectroscopy (EIS). The foundations for the concept will be outlined, and rudimentary (preliminary) results will be shown. Limitations and opportunities will be discussed and some future plans for continuing work will be addressed.

Electromagnetic Materials State Awareness Monitoring, Peter B. Nagy, University of Cincinnati

Electromagnetic methods offer unique opportunities for materials state awareness monitoring. A variety of sensors can be built based on electric, magnetic, electromagnetic, and thermoelectric principles. These very simple and robust sensors can detect and quantitatively characterize subtle environmentally-assisted and/or service-related changes in the state of metals, such as microstructural evolution, phase transformation, plastic deformation, hardening, residual stress relaxation, increasing dislocation density, etc. In most cases, the detection sensitivity is sufficiently high for the purposes materials state awareness monitoring and the feasibility of the sensing method is mainly determined by its selectivity, or the lack of it, to a particular type of damage mechanism.

Nonlinear Ultrasonic Materials State Awareness Monitoring, Larry J. Jacobs and Jianmin Qu, Georgia Institute of Technology

This talk presents an overview of recent progress on the use of nonlinear ultrasonic techniques to quantitatively characterize material state. In particular, this talk will focus on methodologies that are based on measuring higher order harmonics to track microstructure changes in the material due to fatigue damage. As a single frequency wave propagates in a material with damage, higher harmonic frequencies are generated. This higher harmonic generation is quantified with an absolute nonlinearity parameter β. Recent experimental measurements have indisputably established the close correlation between β and the degree of damage. Since □ can be measured using nonlinear ultrasound, such a correlation enables the nondestructive characterization of the fatigue life of a metallic component. Various nonlinear ultrasonic techniques based on bulk, Rayleigh and Lamb waves will be discussed and reviewed. Measurement results will be presented for aluminium alloys and Ni-base super alloys subjected to quasi-static monotonic tension and low-cycle fatigue. Recent progress on developing quantitative physics-based models

to relate □ to material microstructure changes has followed two somewhat different approaches. One is to directly relate □ to the dislocation substructure, and the other is to relate □ to cumulative plastic strain developed in the material. The former provides a clear physical interpretation of □ while the latter allows for the characterization of material state and the estimation of the remaining fatigue life of a component based on nondestructive nonlinear ultrasonic measurements. Both approaches will be discussed and their predictions are compared to experimental measurements.

Session 6, Technical Capabilities
Mark J. Schulz, Chairperson

Exploring the implications of a Bayesian approach to Materials State Awareness, Bruce Thompson, Iowa State University

Materials State Awareness has, at its end goal, the probabilistic prognosis of the state and future serviceability of materials components, structures and systems. Many tools are seen as providing inputs to this prediction, including models of damage evolution, direct measurements of the operational environments of individual structural components and systems (as opposed to fleet averages) which provide input to those predictions, and sensing the evolution of the state using either local or global sensors. This paper will address the challenge of integrating this disparate information, with emphasis on the sensing aspects, into a probabilistic prediction of the future service life and performance of the component/system. It is argued that a Bayesian approach, in which a priori knowledge of possible states is narrowed by the information available from sensors, is an attractive approach to realize the goal. Examples will be given that illustrate some of the key issues.

An Interdisciplinary to Understanding "Dwell Fatigue" in Ti Compressor Rotor Alloys, Jim Williams, Amit Bhattacharjee, Somnath Ghosh, Mike Mills, and Stan Rokhlin, Ohio State University

There is a fatigue failure mode in high temperature Ti alloys known as "Dwell Fatigue". This mode is characterized by a major reduction (more than an order of magnitude) in fatigue life when the material is subjected to a loading pattern where the load is held at maximum value for a dwell period, typically several minutes. Further, this failure mode is typified by subsurface crack initiation which complicates detection of early stages of failure during field inspections. Because of its importance, the phenomenology of dwell fatigue has been thoroughly examined and is well defined. However, the fundamental reasons for the occurrence of dwell fatigue are not well understood. This talk will first describe the phenomenology of dwell fatigue. Following this, results of a multi-year, interdisciplinary study of dwell fatigue in Ti-6Al-2Sn-4Zr-2Mo (+Si) will be described. The study has used solid mechanics modeling, detailed characterization methods and high resolution acoustic microscopy to provide a fundamental, semi-quantitative understanding of dwell fatigue. An important aspect of this failure phenomenon includes internal load re-distribution during the hold time at maximum load. This load re-distribution is caused by variations in stress relaxation rate as a function of local crystallographic orientation. This orientation dependence relative to the loading direction influences the degree of load re-distribution. The role of microtexture or regions of common alpha phase orientation on the

reduction in fatigue life during dwell loading has been shown. Qualitative relationships between microtexture and dwell fatigue susceptibility will be described. The current state of understanding and future directions to develop a quantitative understanding will also be described.

An Unified Approach to Structural Health Management and Damage Prognosis of Metallic Aerospace Structures, Aditi Chattopadhyay, Arizona State University

A comprehensive framework on structural health management (SHM) and damage prognosis of metallic aerospace components is being developed to provide reliable life cycle estimates of metallic aerospace components (AFOSR MURI). The procedure comprises a hierarchical framework of sensor data, information management, models and algorithms that span and integrate scales from microstructure to structural level. The methodological developments are being steered by closed-loop validations, incorporating both simulation and experimental test data. Specific research concentrations include: i) Physically-based multiscale modeling; (2) Models for in situ interrogation and detection; (3) Prognosis via state-awareness and life models. The methodological developments are steered by a closed-loop validation plan that incorporates both simulation and experimental test data. Representative results will be presented to provide an overview of this MURI project in the areas of multiscale modeling, damage classification and structural damage prognosis.

Damage State Awareness in Composite Laminates Via Ultrasonic Guided Waves, Cliff Lissenden and Joe Rose, Pennsylvania State University

As the amount of composite materials used in aircraft increases, so must our ability to monitor the damage state in composites. Ultrasonic guided wave based methods are attractive because they are capable of monitoring large regions from one location. However, the multilayered anisotropic nature of composite laminates makes guided wave propagation quite complex. The ability to understand guided wave excitation and propagation is fundamental to a physically based monitoring system that makes best use of activation, sensing, and signal processing capabilities. Penetration power and sensitivity improvement are the major challenges in guided wave based technologies for detection and quantification of structural damage in composites. We present a physically based understanding of ultrasonic guided wave propagation and excitation behaviors in composites, which is an essential building block for system design.

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VIII Initial Draft

Prognosis of Aircraft and Space Devices, Components, and Systems

Discovery Challenge Thrust (DCT)

Background: The USAF missions in air and space rely on the reliability of complex systems that range from aircraft and space platforms to electronic devices and sensors. Materials in these systems include a wide variety of metals, composites, polymers, and ceramics and combinations thereof ranging in forms from nanoscale quantum structures, to films and coatings, to complex structural components and structural assemblies. It is critical that these systems perform as designed for extended periods of time (much beyond their original design life). Past design practices have relied on various methodologies from safe-life to damage tolerance to reliability-based metrics such as mean time between failures (MTBF) for electronic components. Original predictions of performance for in-service applications have often been inadequate resulting in high costs for maintenance and repair, lack of availability or readiness, and in some cases loss of crew. Responses to these short-comings include in-service inspection requirements such as for aircraft structural integrity (ASIP), mandated corrosion inspection and repairs, line replacement unit upgrades in avionics, and various reliability improvement programs.

In no case are we able to predict by component serial number or other "finger print" identification of a device or component in a complex system when that device or component is reaching a state where it must be replaced or repaired. Instead, for systems we rely on system or fleet averages driven by the statistics of the lower tail of the reliability distribution. The USAF relies on statistically variable inspection methods for components that require large levels of damage in the form of cracks or visible corrosion in order to have a reasonable likelihood of finding the damage before component and system failure occurs. Great expense to the USAF occurs as a result of unnecessary and damaging inspections driven by worst-case conditions. Repetitive inspections are required to give a needed level of confidence that the damage state has not been missed.

This methodology and mind-set has driven the entire field of component and system reliability for non-electronics to focus the research on end-of-life scenarios – large cracks and extensive corrosion, for example. In the field of electronics, line replaceable unit (LRU) actions are driven by an assumption that all LRUs behave at the level of the worst case. Space electronics do not even allow for replacements! Reusable space access platforms such as the national space transportation system orbiter will end up requiring extensive ground time between missions to assure reliably the ability to launch the next mission for that platform.

The USAF needs the ability to design and deploy devices, components, and systems based on: (1) the ability to accurately predict with (defined) confidence the performance by serial number or other identifying "finger print"; (2) accurate prediction with defined confidence of future performance capability and potential degradation in near real-time; (3) actionable information to

the operator so that corrective actions can be taken in a timely manner to assure mission completion and minimize operating cost and risk.

Problem: Determine in real time the current state of a uniquely-identified device, component or system with a defined degree of confidence such that the remaining capabilities of that system or component can be predicted with a high degree of accuracy and known level of confidence for any material systems or material combinations, material processing, operational environments, component usage history, and failure or material/structure/system degradation mode.

Technology Challenges: In view of the above problem and realities, the following taxonomy of critical future technology challenges has been identified:

1. Determine and assess early and progressive changes in material state associated with operational usage and exposure (again, any material and scale appropriate to the various damage states that must be captured).
    1. Since the final failure location in any device, component, or system is most likely to be unobserved, any local state sensing must be able to map across the entire device, component, or system based on a suitable model thereof for all potential failure states for any internal and interface locations.
    2. Fundamental innovations in traditional non-destructive evaluation for state awareness are required. Physics-based material-state sensing including novel signal processing technology applicable to unique mechanism detection and characterization through state change detection that include damage detection, material and damage state characterization need to be developed.
    3. All state sensing or characterization models must provide actionable interpretation in terms of device, component, or system capability in near real-time such that combinations and synergisms of state changes are fully captured.
    4. Strategies are needed to define optimum combinations of state awareness sensing and virtual (computational model-based) "sensing" are needed to define integrated system health management architectures.
2. Accurately predict the real-time physical, chemical or electronic state at any location for complex systems subject to hysteresis, damping, degradation, cyclic loading, thermal and environmental exposure over time, the predictions leading to state awareness.
    1. State awareness and capability prognosis at any level must be able to be queried as needed for device, component, or system future capacity and reliability.
    2. State awareness must include the ability to determine with defined confidence measures the existence of "hot spots" of damage or deterioration based on remote measures.

   3. Modeling systems must be capable of multi-scale nonlinear representations of all state condition and processes and allow for full validation strategy development and demonstration.

3. Relate the current and evolving state of microstructure and damage processes at various length scales that will enable comprehensive probabilistic prognosis modeling of the material/structural/system state. Consider the following as a partial list of variables for state modeling:

   1. Role of surface and interface material state changes and interactions associated with machining, surface treatments, films, coatings, cyclic hardening and softening, and environmental interactions critical to device, component, and system response and reliability.

   2. Depending on the material system and operational-environment conditions, gradients and linkages across materials and interfaces, time and physical scales, physical and chemical processes, and other local variables and conditions critical to mechanism-based modeling at the device and component level could be considered,.

   3. Uncertainty and variability effects must link to the physics/chemistry and mechanics in order to accurately account for response variability effecting device, component and system reliability and model confidence.

   4. Processing, state evolution modeling and remaining capability prognosis must be provided in an end-to-end linkage to operational usage and environmental exposures such that the critical, physics-based parameters can be linked back to the original material processing conditions.

   5. Interactions and synergisms between processing and intrinsic material state must be accounted for at the appropriate scales based on physics-based modeling.

   6. Ability of devices, components, and systems to be aware of various regeneration, recover, heal, etc. and to communicate and participate in autonomic behavior is needed to assure the capability for fulfilling the original mission in the presence of damage or degradation.

Ability to reason through discontinuous past experiences including repair, autonomic response, and other system influences in the presence of current state awareness is needed in order to reliably predict future states with defined confidence measure at the device, component, or system level.

IX Ballot for Priorities

Prognosis of Aircraft and Space Devices, Components, and Systems

Discovery Challenge Thrust (DCT)

Background: The USAF missions in air and space rely on the reliability of complex systems that range from aircraft and space platforms to electronic devices and sensors. Materials in these systems include a wide variety of metals, composites, polymers, and ceramics and combinations thereof ranging in forms from nanoscale quantum structures, to films and coatings, to complex structural components and structural assemblies. It is critical that these systems perform as designed for extended periods of time (much beyond their original design life). Past design practices have relied on various methodologies from safe-life to damage tolerance to reliability-based metrics such as mean time between failures (MTBF) for electronic components. Original predictions of performance for in-service applications have often been inadequate resulting in high costs for maintenance and repair, lack of availability or readiness, and in some cases loss of crew. Responses to these short-comings include in-service inspection requirements such as for aircraft structural integrity (ASIP), mandated corrosion inspection and repairs, line replacement unit upgrades in avionics, and various reliability improvement programs.

In no case are we able to predict by component serial number or other "finger print" identification of a device or component in a complex system when that device or component is reaching a state where it must be replaced or repaired. Instead, for systems we rely on system or fleet minimums driven by the statistics of the lower tail of the reliability distribution. Great expense to the USAF occurs as a result of unnecessary and damaging inspections driven by these worst-case limits. Repetitive inspections are required to give a needed level of confidence that the damage state has not been missed.

This methodology and mind-set has driven the entire field of component and system reliability for non-electronics to focus the research on end-of-life scenarios – large cracks and extensive corrosion, for example. In the field of electronics, line replaceable unit (LRU) actions are driven by an assumption that all LRUs behave at the level of the worst case. Space electronics do not even allow for replacements! Reusable space access platforms such as the national space transportation system orbiter end up requiring extensive ground time between missions to assure reliably the ability to launch the next mission for that platform.

The USAF needs the ability to design and deploy devices, components, and systems based on: (1) the ability to accurately predict with defined confidence the performance by serial number or other identifying "finger print"; (2) accurate prediction with defined confidence of future performance capability and potential degradation in near real-time; (3) actionable information to the operator so that corrective actions can be taken in a timely manner to assure mission completion and minimize operating cost and risk.

Prognosis Basis: Prognosis as a vision for a future capability is based on the integration of three distinct and required technology elements and an integration of these three elements, as follows:

1 Comprehensive, robust and accurate physical, environmental, and operational state awareness (i.e., sensing) for complex systems of mechanical elements such as air or space platforms composed generally of built-up structures with multiple elements including three dimensional geometric complexity with materials ranging from monolithic and layered materials to fully-engineered material systems over a wide range of physical scales from the microscopic (e.g., electronics) to the macroscopic (e.g., aircraft).

2 Material systems behavior models that are capable of accurate, probabilistic predictions of the evolution of the material property and damage states as a result of external environments including mechanical, atmospheric, and thermal load conditions over the system's full history that starts with material fabrication and component processing through to long-term operational usage.

3 Robust structural modeling and/or simulation capability at scales ranging from the microscopic to the macroscopic (and global/local combinations thereof) that fully and accurately capture the variabilities and uncertainties associated with known and unknown sources of variability in item 2, above, and uncertainty drivers which, in combination with item 1, can operate as virtual experiments capable of replacing currently-required physical testing for design validation.

4 Integration of these items to achieve reliable prognosis of future system state conditions and reliability through the synergistic application of the three basis items above such that system reliability for expected or future system utilization can be accurately forecast along with the uncertainties (or confidence) in the predicted state outcomes. It is expected that some prognosis capability is possible only by combinations of 2 or 3 of these bases operating synergistically.

Basic Research Challenges: In view of the above problems and realities, the following taxonomy of critical future technology challenges has been identified.

<u>1 Geometrically and Materially Complex System State Awareness through Sensing</u>

a) Detect and characterize real-time comprehensive environmental conditions (e.g., external boundary conditions) in potentially harsh environments. Supports 3 and 4, above.

b) Provide comprehensive local characterization of microstructural material changes capable of providing a globally selective and evolving "fingerprint" of the material state in support of damage evolution modeling.

c) Capture and then distinguish between evolving microstructural mechanisms in order to detect key damage mechanisms within complex built-up structural features.

d) Overcome the local damage localization problem for damage in complex, built-up structural systems where the damage location is inaccessible and relatively unknown using large-scale interrogation and state sensing strategies.

e) Define break-through sensor capabilities that overcome the challenges of providing light-weight, autonomous, long-life, and reliable sensing in harsh thermal and other environmental conditions.

f) Exploit the concept of physics-based modeling of sensor performance characteristics, external environmental conditions and simulations of damage evolution (Item 3) to create reliable and robust virtual sensors of material state.

g) Develop state awareness strategies and local implementations that characterize the material state at both the mean and tail of the probabilistic damage conditions.

h) Generate an intelligent, experience-based sensing strategy that characterizes the type and extent of corrosion locally but from a large scale structural perspective.

i) Create a self-validating and calibrating sensing architecture with the ability to determine its probability for false calls.

j) Provide a capability to rapidly characterize intrinsic defect distributions applicable to large material acquisitions.

k) Provide the ability to determine with defined confidence measures the existence of "hot spots" of damage or deterioration within complex structural systems based on remote measures.

<u>2 Material system state and damage modeling.</u>

a) Define the global and local damage parameters appropriate to future, complex engineered material systems (what to measure, when and where).

b) Generate physics-based damage models for complex physical and engineered material systems.

c) Develop material state and damage progression through synergistic application and exploitation of today's NDE tools.

d) Create micromechanics-based material state and damage evolution models that predict the variability within macro-mechanical damage models, emphasizing the likely minimum life mechanisms.

e) Establish fundamental material simulation methods capable of providing accurate predictions of material state and damage evolution – virtual material characterization testing – that defines mean and minimum behavior characteristics including effects of material processing and component manufacturing.

f) Provide validated and accurate quantitative simulation tools for material properties and damage mechanism evolution for complex, engineered material systems.

g) Provide scalable damage evolution models that span the full size range of the damage from manufacturing and processing through end of life.

h) Establish the role of surface and interface material state changes and interactions associated with machining, surface treatments, films, coatings, cyclic hardening and softening, and environmental interactions critical to device, component, and system response and reliability.

i) Simulate and validate models for the interactions and synergisms between processing and intrinsic material state that must be accounted for at the appropriate scales based on physics-based modeling.

j) Create material systems that are capable of self-reporting of material and interface states through remote interrogations.

<u>3 Robust structural modeling and/or simulation capability</u>

a) Provide the ability to accurately predict the probabilistic response of complex local features within very large-scale structural modeling for systems composed of various length scales from microscopic to aircraft size.

b) Provide probabilistic structural modeling system capable of accurately simulating the response of a real aircraft to external loading that includes widely distributed slip and hysteresis associated with tolerances, shims, fits, and other sources of local nonlinear behavior.

c) Exploit the simulation of global/local aircraft state sensing with advanced probabilistic structural modeling to achieve a virtual aircraft model capable of near real-time hot spot localization.

d) Develop a robust and reliable damage evolution modeling capability for damage growing from the predicted initiation site to the aircraft failure conditions.

e) Create a highly effective, large-scale finite structural modeling capability that includes key variability inputs such as manufacturing variances such that model updating is provided through global sensing and system response.

4 Integration to achieve reliable prognosis of future system state conditions and reliability

a) Provide integration strategies capable of fusing the probabilistic state awareness information and damage evolution models while providing key sensitivity factors and engineering confidence intervals on the simulation with effective strategies for field updating of the original design responses.

b) Provide integration strategies capable of fusing multiple failure modes and locations in complex structural systems such as at the aircraft level.

c) Provide probabilistic fusion of state awareness results with simulation analyses of material systems behavior where all elements involve probabilistic conditions and other sources of uncertainty to achieve a decision on future remaining life with confidence intervals that accurately portray the roles of each the important factors in validating the remaining life prediction.

d) Provide a system-level self-assessment strategy that identifies errors or shortcomings in any one of the three key bases sufficient to drive a fundamental update in any of the three basis models.

X Ballot Results

	1											2										3					4			
name	1a	1b	1c	1d	1e	1f	1g	1h	1i	1j	1k	2a	2b	2c	2d	2e	2f	2g	2h	2i	2j	3a	3b	3c	3d	3e	4a	4b	4c	4d
Blodgett, Mark		9	8		7				2										6	4				3	5		10		1	
Bossi, Richard											6	10		9							2		7		4		8	5	3	
Chona, Ravi																		6				7	3	4	8	1	5	9	10	2
Christodoulou, Julie[1]																														
Cruse, Thomas	6	7		10	2									1	5	9						4	8				3			
Derriso, Mark	3			9							8	10				2							7	6	5			4	1	
Fredell, Robert Col.[1]																														
Gallagher, Joe[2]																														
Gangloff, Rick	8										1	2			9	4	10		5			3			7				6	
Gonzalez, Jorge[1]																														
Grandt, Alten (Skip)	10	1		6							8	9		5							2				4			3		7
Hassan, Waled		10	8		7							9		6	5							3	4					2	1	
Hindle, Edmund	7				10	9	8		5			6	1	4					2								3			
Jacobs, Laurence		10	9	3		8					7	5	4	6								2			1					
Jata, Kumar		9		10	6		7			8			2	5	4			3					1							
John, Reji		9				6	4			1				5	10	8			7			2			3					
Jones, Wayne		10	9		5					6					8	7	1						4		3	2				
Kerans, Ron		8				1					6	9					10			2	5	3		4					7	
Larsen, James					10	5	7		3						9	6	8	2								1			4	
Lee, Byung-Lip (Les)[1]																														
Lindgren, Eric[2]																														
Lissenden, Cliff	4		2	10	5						8	3		9											6			1	7	
McDowell, Dave			9		5		4			3					10	7			8						2		6		1	
Michaels, Jennifer		9	7	10							8		1	5		4	2								6	3				
Miller, Matthew					2	9				8		10			3	7						6			4			5	1	
Millwater, Harry						3	1				4				6	5	2							8		7	10		9	
Nagy, Peter	1	9	7		10				2			8	4		3									6			5			
Qu, Jianmin		10	8	3		9					4	7		6					5			1		2						
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Rollett, Anthony						5	3			4	1	2	8			9						7				6	10			
Ruffing, Kent				6	3						8		1	2		5							9	7	4		10			
Schulz, Mark		6		8	9									7							10									
Thompson, Bruce		6	8			7	2			1		9		5				3						4			10			
Tuegel, Eric J.				4								3						5				6		8	7	1		9	10	2
Wawrzynek, Paul "Wash"		4				6							9		10			5		1		8	7		3		2			
Williams, James					4		9			7		10			2	8						3			5			6	1	
Williams, Jeffrey[2]																														
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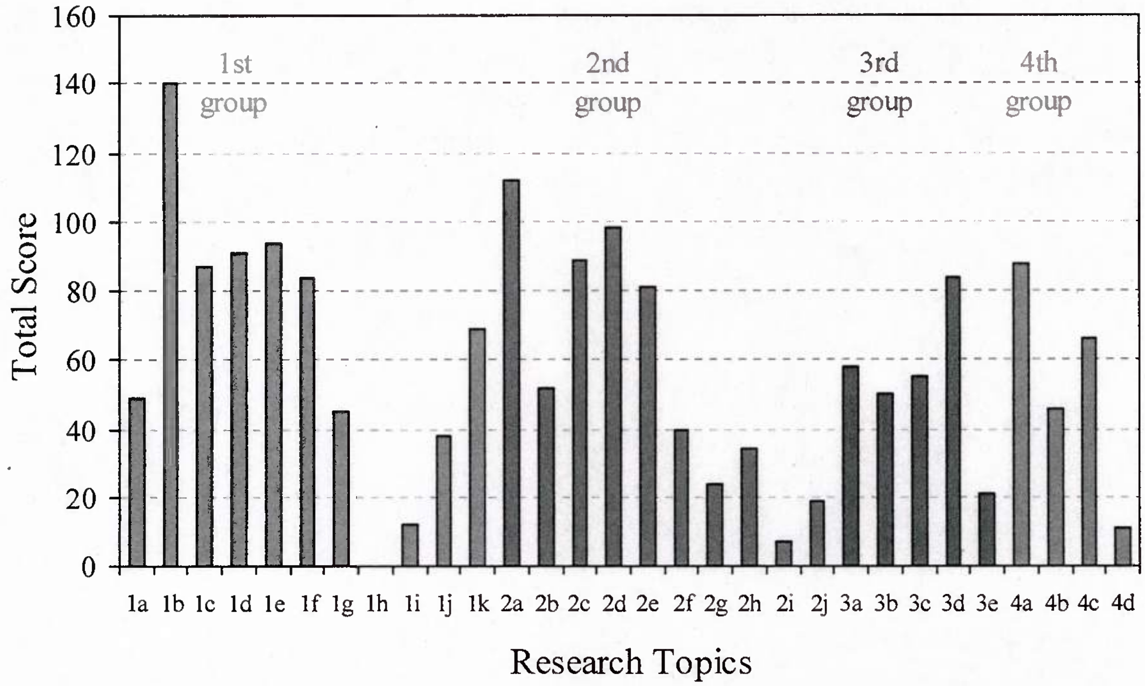
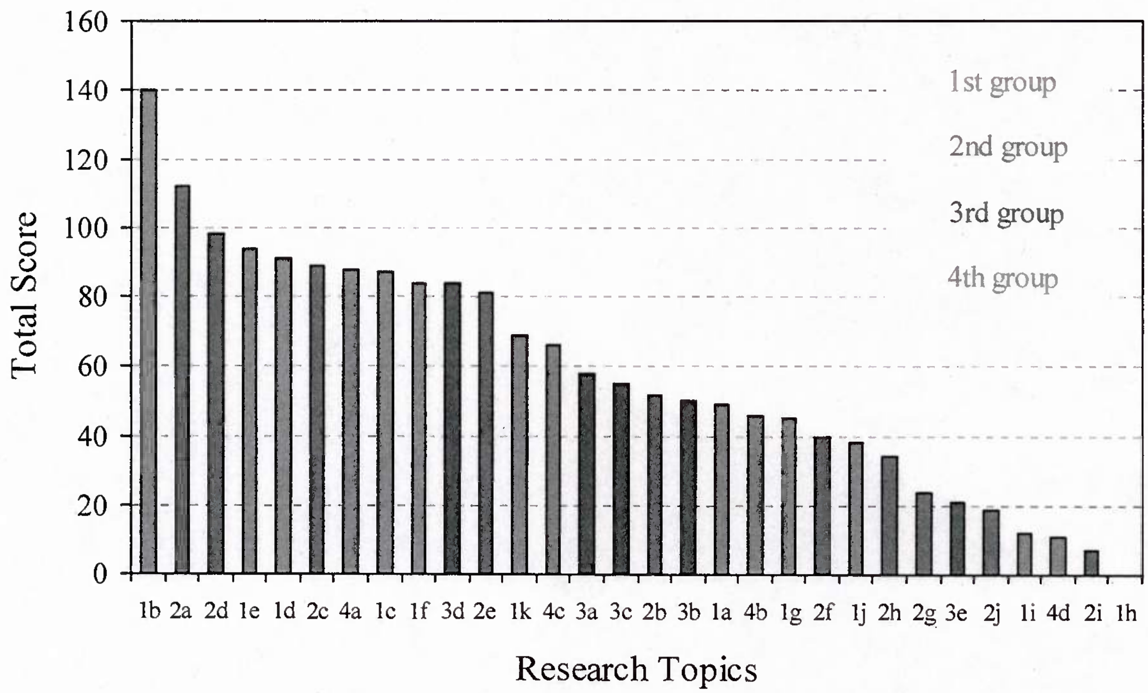
voting attendees 39 (without Victor Giurgiutiu), voted 32, [1]did not respond 4, [2]abstained 3, did not attend 2 (Chattopadhyay, Aditi and Pratt, David M.)

Combined Ballot Results



Rankings



XI Final Recommendations

The following is a list of the final recommendations of the workshop participants (color-coded according to the previously introduced scheme).

1. Geometrically and Materially Complex System State Awareness through Sensing

    a. Provide comprehensive local characterization of microstructural material changes capable of providing a globally selective and evolving "fingerprint" of the material state in support of damage evolution modeling.
    b. Define break-through sensor capabilities that overcome the challenges of providing light-weight, autonomous, long-life, and reliable sensing in harsh thermal and other environmental conditions.
    c. Overcome the local damage localization problem for damage in complex, built-up structural systems where the damage location is inaccessible and relatively unknown using large-scale interrogation and state sensing strategies.
    d. Capture and then distinguish between evolving microstructural mechanisms in order to detect key damage mechanisms within complex built-up structural features.
    e. Exploit the concept of physics-based modeling of sensor performance characteristics, external environmental conditions and simulations of damage evolution (Item 3) to create reliable and robust virtual sensors of material state.
    f. Detect and characterize real-time comprehensive environmental conditions (e.g., external boundary conditions) in potentially harsh environments. Supports 3 and 4, above.
    g. Develop state awareness strategies and local implementations that characterize the material state at both the mean and tail of the probabilistic damage conditions.
    h. Generate an intelligent, experience-based sensing strategy that characterizes the type and extent of corrosion locally but from a large scale structural perspective.
    i. Create a self-validating and calibrating sensing architecture with the ability to determine its probability for false calls.
    j. Provide a capability to rapidly characterize intrinsic defect distributions applicable to large material acquisitions.
    k. Provide the ability to determine with defined confidence measures the existence of "hot spots" of damage or deterioration within complex structural systems based on remote measures.

2. Material system state and damage modeling.

    a. Define the global and local damage parameters appropriate to future, complex engineered material systems (what to measure, when and where).
    b. Create micromechanics-based material state and damage evolution models that predict the variability within macro-mechanical damage models, emphasizing the likely minimum life mechanisms.
    c. Develop material state and damage progression through synergistic application and exploitation of today's NDE tools.

d. Establish fundamental material simulation methods capable of providing accurate predictions of material state and damage evolution – virtual material characterization testing – that defines mean and minimum behavior characteristics including effects of material processing and component manufacturing.
e. Generate physics-based damage models for complex physical and engineered material systems.
f. Provide validated and accurate quantitative simulation tools for material properties and damage mechanism evolution for complex, engineered material systems.
g. Provide scalable damage evolution models that span the full size range of the damage from manufacturing and processing through end of life.
h. Establish the role of surface and interface material state changes and interactions associated with machining, surface treatments, films, coatings, cyclic hardening and softening, and environmental interactions critical to device, component, and system response and reliability.
i. Simulate and validate models for the interactions and synergisms between processing and intrinsic material state that must be accounted for at the appropriate scales based on physics-based modeling.
j. Create material systems that are capable of self-reporting of material and interface states through remote interrogations.

3. Robust structural modeling and/or simulation capability

a. Develop a robust and reliable damage evolution modeling capability for damage growing from the predicted initiation site to the aircraft failure conditions.
b. Provide the ability to accurately predict the probabilistic response of complex local features within very large-scale structural modeling for systems composed of various length scales from microscopic to aircraft size.
c. Provide probabilistic structural modeling system capable of accurately simulating the response of a real aircraft to external loading that includes widely distributed slip and hysteresis associated with tolerances, shims, fits, and other sources of local nonlinear behavior.
d. Exploit the simulation of global/local aircraft state sensing with advanced probabilistic structural modeling to achieve a virtual aircraft model capable of near real-time hot spot localization.
e. Create a highly effective, large-scale finite structural modeling capability that includes key variability inputs such as manufacturing variances such that model updating is provided through global sensing and system response.

4. Integration to achieve reliable prognosis of future system state conditions and reliability

a. Provide integration strategies capable of fusing the probabilistic state awareness information and damage evolution models while providing key sensitivity factors and engineering confidence intervals on the simulation with effective strategies for field updating of the original design responses.

b. Provide integration strategies capable of fusing multiple failure modes and locations in complex structural systems such as at the aircraft level.
c. Provide probabilistic fusion of state awareness results with simulation analyses of material systems behavior where all elements involve probabilistic conditions and other sources of uncertainty to achieve a decision on future remaining life with confidence intervals that accurately portray the roles of each the important factors in validating the remaining life prediction.
d. Provide a system-level self-assessment strategy that identifies errors or shortcomings in any one of the three key bases sufficient to drive a fundamental update in any of the three basis models.